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Antenna Size, Transmitter Power, and Solid State Transmitter Considerations in Affordable Radar Design

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Variant radar system configurations are explored aimed at reducing the radar production cost. The study baseline uses the Volume Surveillance Radar concept, a long range, 3-D shipboard air surveillance radar using pulsed doppler processing techniques. The variants adjust the relative performance of the individual radar subsystems, primarily the antenna, transmitter, and number of receiver channels. When no deterioration in the overall radar performance is permitted, the possible savings in production cost are limited to 7% except for the use of a solid state on-mount transmitter which offers a potential savings of 16%. When minor performance reductions in data rate, operating frequency bandwidth, or elevation coverage are permitted, production cost savings of up to 32% may be achieved.

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ANTENNA SIZE, TRANSMITTER POWER, AND SOLID STATE TRANSMITTER CONSIDERATIONS IN AFFORDABLE RADAR DESIGN

1. Introduction

The major thrust in modern radar design is toward achieving better performance, a trend that generally results in more complicated, technologically more advanced, and consequently more expensive solutions. Typical specifications call for high probabilities of detection of small cross section targets in severe natural and electronic countermeasure (ECM) environments. Radar systems designed to meet such requirements typically feature high transmitted powers, phased array antennas with large apertures and a large number of array elements, pulse compression for good range resolution, signal processing with very high throughput rates, and adaptive data processing and control capabilities.

While the performance of modern radars has indeed improved dramatically, their costs of acquisition and operation have also increased sharply [1]. In many cases the procurement costs of the latest state-of-the-art systems exceed current budgetary constraints. The Affordable Radar Study investigates cost-effective designs as a way of reducing costs while maintaining the original system performance and satisfying the operational system requirements. This phase of the Affordable Radar Study focused on the Volume Surveillance Radar, and considered ways of reducing the cost of that radar.

The Affordable Radar Study explores possible design approaches that may result in lower production costs. The fundamental guideline for the study is that no compromise in radar performance is permitted. Therefore, initially only design variants that met this condition were considered. Cost savings were limited, however, (except for an antenna mounted solid state transmitter) and additional studies were undertaken to see how much costs could be reduced with only moderate performance degradation. In terms of radar characteristics, the no-performance-compromise requirement can be translated into the following conditions:

- Maintain the detection range in clear, clutter and ECM environments,
- Maintain radar data rate and coverage, and
- Maintain radar resolution (range, angle, and doppler).

The metric for determining the desirability of a particular radar variant is a comparison of the estimated production cost of that design variant with the cost of the baseline radar system. Design variants that result in significant predicted production cost savings represent attractive alternatives to the baseline radar implementation. The Affordable Radar Study does not address the difference in the development costs of the alternate radar configurations.

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Reliable production cost estimates generally are obtained by pricing of detailed parts lists and, whenever possible, drawings. Such an approach is not feasible for this study, as designs for the various subsystems are not available either for the baseline system, or for any of the possible variants. Cost estimation must rely on subsystem characteristics and parameters, as well as on comparisons with cost data for similar systems having comparable complexity and using essentially the same technology.

The model used for estimating preliminary radar production cost is the Tecolote Model [2] which was developed from data from about a dozen different radars. It uses a large number of parameters in cost estimating relationships (CERs) for scaling the costs of each of the different subsystems to arrive at an estimate for the variant system. The cost model,which is based on the technology of the 60s and 70s, is inadequate to estimate the costs of modern radars. The estimated processor costs, for example, are especially low for complex doppler radar processors. The cost predictions of the model have been adjusted based on the collective judgment of the study participants and industry inquiries to reflect better the realities of current production costs.

2. Study Approach and Methodology

The initial study task was to examine the performance of the Volume Surveillance Radar and to determine a production cost estimate to be used as the baseline for evaluating the costs of variant configurations resulting from the Affordable Radar Study.

The Volume Surveillance Radar is a modern, long range, multi-beam L-Band shipboard air search system for the detection of airborne attackers, for threat evaluation, and for accurate designation to engagement systems. The system employs pulsed doppler techniques and is designed to operate in a severe clutter environment. It has a rotating low sidelobe antenna which is electronically steered in elevation. The baseline concept requires a high average power transmitter and a complex signal processor for multiple channel doppler processing.

The Affordable Radar Study trade-offs concentrated on exploring the potential for cost savings by varying the relative performance levels of the major subsystems of the Volume Surveillance Radar. The following variants were included this effort:

- Antenna size versus transmitter power
- Collocated transmitter and antenna
- Tube-type versus solid state transmitter

Additional trade-offs planned for future studies include:

- Frequency selection
- Low sidelobe antenna versus sidelobe cancelers
- Effect of number of elevation beams

Based on the results of the trade-off studies, variant configurations of the Volume Surveillance Radar have been identified and their cost estimated. This procedure resulted in a comparison of the overall system production cost for variants having different levels of performance of the various individual subsystems. The variation of subsystem cost with performance had to be estimated.

3. Volume Surveillance Radar Baseline

The Volume Surveillance Radar used as the baseline system for the Affordable Radar Study is an L-Band multibeam long-range shipboard radar designed to provide 3-D target information for the early detection, threat-evaluation and designation of airborne targets for engagement by the fire control system. The radar uses high-PRF pulsed doppler techniques and has no velocity ambiguities over the range of all incoming target velocities of interest. High speed, threatening targets are rapidly identifiable and can be designated for immediate engagement.

A reference detection range for the Volume Surveillance Radar has been evaluated for the parameters listed in Table I. The reference detection range has been calculated on a 1 sq. meter Swerling I fluctuating target for a 0.5 probability of detection at the peak of the lowest elevation beam at the mid-band frequency of 1150 Mhz. For this condition, and a false alarm rate of 10^{-7}, corresponding to about 1 false alarm per scan per beam, a 13.5 dB single pulse signal to noise ratio is required. The reference detection performance is based on the coherent processing of a single 32-pulse burst which is treated as a single pulse. As shown on the attached Blake chart, Figure 1, with a detection criterion of seeing the target on a single coherent processing interval (CPI) and a corresponding 13.5 dB visibility factor, a free space range of 129 nmi is predicted. When atmospheric attenuation is included, the reference detection range on this 1 sq. meter Swerling I target becomes 124 nmi.

TABLE I Radar Parameters for the Baseline Volume Surveillance Radar

Frequency, Mean	1150 MHz
Average power	30 Kw
Antenna size	24' wide x 8' high
Beamwidth, Azimuth	2.6 degrees
Beamwidth, Elevation	8 degrees
Antenna type	Array, phase scan in elevation
Azimuth scan	Mechanical scan
Azimuth scan period	5 sec
# of elevation beams	4
Elevation scan	Sequential scan
Transmitter	Off-mount
Noise figure	2 dB

PULSE-RADAR RANGE-CALCULATION WORK SHEET (L.V. Blake)		
Radar: VOLUME SEARCH RADAR (OFF-MOUNT SS-XMTR) Elevation Angle: 4 Sw.C. 1		P_d= 0.5 P_f= 1.00E-07

A. Computation of T_s	B. Range Factors	C. Decibel Values
(a) Sky Temperature = 70.0 °K Ant. Ohmic Loss L_a= 2.70 dB Antenna Temp. T_a=186.5 °K	P_{av}(kW)= 30.00 $t_f(\mu s)$= 4,116.0 G_t = G_r = σ(sqm) = 1.000 f(MHz) = 1,150.0 T_s(°K) = 545.7 V_o = 1 of 1 CPI C_B = L_t = L_p = L_x =	10 log(P_{av}) = 14.77 10 log(t_f) = 36.14 G_t(dB) = 29.80 G_r(dB) = 29.80 10 log (σ) = 0.00 -20 log(f) = -61.21 -10 log(T_s) = -27.37 $-V_o$(dB) = -13.50 $-C_B$(dB) = -0.50 $-L_t$(dB) = -1.50 $-L_p$(dB) = -0.70 $-L_x$(dB) = -5.80 Rng Eq Cnst = 4.45
(b) Receive Loss L_r = 1.50 dB Equiv. Temp T_r =119.6 °K		
(c) Noise Figure F_n = 2.00 dB Equiv. Temp. L_rT_e=239.5 °K	Net Decibels (dB) = 4.38	
	F.S. Detection Range (nm) = 128.7	
Syst. Noise Temp. T_s=545.7 °K	F.S. Detection Range (km) = 238.3	

Atmosph. attenuation corresponding to free-space range	L_a(dB) = 0.67
First approximation to actual detection range	R_{max}(nm) = 123.9 R_{max}(km) = 229.4
Atmosph. attenuation for first range approximation	L_a(dB) = 0.67
Second approximation to actual detection range	R_{max}(nm) = 123.9 R_{max}(km) = 229.4

Fig. 1 Blake Chart for the Baseline Volume Surveillance Radar

The antenna gain is calculated for the 24' x 8' antenna with a tapered illumination with -45 dB sidelobes. Including the antenna ohmic losses of 2.7 dB, the net gain at the antenna port of the rotary joint is 29.4 dB.

A radar PRF 11.9 kHz is used resulting in an unambiguous velocity coverage at the mid-band frequency for target velocities up to 1500 m/s. To assure good cancellation of returns from distant clutter, 17 fill pulses are transmitted in addition to the 32 pulses to be processed. The number of fill pulses used is adequate for cancellation of distant clutter out to 120 nmi and 30 KFT. The transient gating loss of 1.3 dB in the lowest beam is based on a 49 pulse transmission which includes 17 fill pulses. Fewer fill pulses are required for the higher elevation beams. A preliminary loss budget is shown in Table II.

TABLE II. Loss Budget

	Elevation power divider	0.3 dB
	Elevation phase shifters	1.8
	Azimuth distribution network	0.6
Total	Antenna	2.7 dB
	Duplexer	0.5 dB
	Rotary Joint	0.7
	Waveguide Xmtr to RJ	0.3
Total	Transmitter/Receiver (Lt/Lr)	1.5 dB
	Filter matching (-70 dB weight)	2.2
	Range gate straddling	1.0
	Eclipsing	0.4
	Transient gating	1.3
	Filter straddling	0.1
	CFAR	0.8
Total	Signal Processing (Lx)	5.8 dB
	Matching loss (CB)	0.5 dB
	Beam shape loss (Lp)	0.7 dB

Because of the high PRF, the measured target range is highly ambiguous. Following initial target detection, additional transmissions are scheduled immediately for target verification and range ambiguity resolution. Alternatively the baseline waveform could be modified to transmit several CPIs with different PRFs on each beam during the total time-on-target (TOT), and the true target range can be calculated based on a detection criterion of seeing the target on at least two CPIs with different PRFs.

4. Trade-off Studies

The trade-off studies explore the relationship between the individual performance requirements of the different radar subsystems while maintaining constant overall system performance as expressed by a constant detection range. Other radar characteristics will inevitably change as the parameters of the individual subsystems are varied. It is assumed that such changes in system performance resulting from variations of the subsystem parameters are kept within acceptable limits.

A major trade-off in the system configuration exists between the transmitter average power and the size of the antenna aperture used. A higher antenna gain achieved by the larger aperture permits a reduction in the transmitter average power. This reduction is calculated based on the energy requirements for target detection, a criterion that does not maintain constant doppler performance and hence is rigorously valid only for non-coherent signal processing. As the antenna aperture increases, the number of pulses available for processing is reduced, and the doppler resolution and clutter cancellation performance of the radar becomes progressively degraded. A system employing pulsed doppler techniques uses coherent signal processing, and the number of pulses per CPI must exceed some minimum value. For the Volume Surveillance Radar at least 24 pulses must be available for processing to obtain the desired clutter suppression performance. To assure the suppression of returns from distant clutter a constant number of fill pulses must also be provided. For the trade-off analysis a minimum of 41 pulses per CPI are used in the lowest elevation beam. This requirement imposes a severe restraint on the suitability of a very large aperture antenna for the Volume Surveillance Radar.

The use of a solid state transmitter in place of a tube-type transmitter has been examined. Although the solid state transmitter may offer attractive life-cycle cost savings, its production cost is not competitive with the tube-type unit. In an off-mount application, a solid state transmitter must have the same power output as a tube-type unit. The use of a solid state transmitter is, therefore, not defensible strictly on a production cost basis. Conversely, an on-mount tube-type transmitter does not appear to be practical for a shipboard radar because of weight, high voltage, and maintainability considerations. An on-mount solid state transmitter, however, is a potentially cost-effective approach because this location results in significantly lower transmit and receive losses that translate into a welcome reduction in the required output power. Provided that satisfactory solutions can be found for weight, cooling and power distribution issues, an on-mount solid state transmitter becomes an attractive alternative.

4.1 Antenna Size vs. Transmitter Power

This trade-off study investigates savings in transmitter average power that can be achieved in the Volume Surveillance Radar by using an aperture larger than the 24 by 8 feet baseline antenna. For a constant detection range, a reduction in transmitted power can be compensated for by an increase in antenna gain. The radar range equation [3] shows that the free space range is proportional to the transmitter power and to the square of the antenna gain [3]. However, a larger antenna aperture results in narrower azimuth and elevation beamwidths, which respectively reduce the time-on-target (TOT) and decrease the elevation coverage of the radar. These effects must be considered when calculating the potential savings in transmitter power that accrue from an increased antenna aperture.

4.1.1 Effects of Changes in Antenna Beamwidths

For a search radar mechanically scanning in azimuth the effects of narrowed beamwidths in azimuth and in elevation are different. A narrower azimuth beamwidth shortens the TOT. The detection logic for a pulsed doppler radar is based on transmitting a number of pulse groups, so-called coherent processing intervals (CPI) during each TOT. When the TOT is shortened because of the narrowed azimuth beamwidth either the number of CPIs or the number of pulses per CPI must be reduced. The number of CPIs must remain fixed so as to keep the chosen detection logic and visibility factor. Therefore, to accommodate the shorter TOT, the number of pulses per CPI must be reduced. Fewer pulses per CPI reduce the integration gain, and this limits the performance advantage that can be derived by increasing antenna gain. The fraction of time of the total TOT allocated to each CPI is kept approximately constant for the different antenna widths considered. The analysis is done only for the lowest beam. The performance of the upper beams will scale in accordance with the percentage of time allocated to each of these beams.

Changes in the elevation beamwidth affect the elevation coverage of the radar. A larger vertical aperture results in a narrower elevation beamwidth and a reduced elevation coverage. The Volume Surveillance Radar has a nominal 8 degree elevation beam, and during each TOT it sequentially executes four elevation scans for a total elevation coverage of about 35 degrees. To maintain the same coverage with a narrower elevation beamwidth, more elevation scans must be made during each TOT. The available TOT must now be shared among more sequential elevation scans, and this further reduces the time available for each individual beam and its several CPIs. As in azimuth, the shortened time that is devoted to each CPI limits the performance advantage available from the increased antenna gain.

Alternatively, several elevation beamwidths could be covered simultaneously by providing parallel receive channels. In this approach the transmit beam must overlap the elevation coverage provided by the simultaneous receive beams. The wider transmit beamwidth results in a lower transmit gain. For the larger antenna apertures dual receive channels are used to preserve the required elevation coverage. A different approach to increasing the TOT is to reduce the azimuth scan rate to compensate for the narrower beamwidth. However, the slower azimuth scan results in a reduced data rate which adversely affects system performance.

Still another approach to improving the time devoted to the lower elevation beams is to use a different waveform at the higher elevation scan angles. A CPI with fewer pulses, or even a longer pulse compression waveform without any doppler processing, may be acceptable at these elevations since here clutter suppression is of lesser importance.

4.1.2 Changes in Parameters

The parameters directly affected by the change in antenna aperture are: antenna gain, antenna ohmic losses, and transient gating loss.

The azimuth and elevation beamwidths, and the directive antenna gain, i.e. not including ohmic losses, for apertures from 16 to 40 feet wide and 8, 12 and 16 feet high are shown in Table III. The values are calculated at 1.1 GHz for -45 dB sidelobes in both the azimuth and elevation planes.

The antenna ohmic losses increase with aperture size. The azimuth distribution network has an assumed loss of 0.6 dB for the 24 foot aperture. The loss in dB is assumed to vary linearly with the aperture width. The elevation power divider loss is assumed to be 0.3 dB for the 8 foot, 0.35 dB for the 12 foot, and 0.4 dB for the 16 foot high apertures.

The transient gating loss [4] results because the transmitted fill pulses are not used in the signal processing. Processing can begin only after the requisite number of pulses have been received from the most distant clutter sources that must be canceled to the full processor capability.

The Volume Surveillance Radar uses 17 fill pulses in the lowest beam to ensure good cancellation of returns from distant clutter. The number of fill pulses is kept fixed throughout the analysis and this constant number assures consistent processing of distant clutter. Since the number of fill pulses in the lowest elevation beam is kept fixed at 17, the number of processed pulses becomes very small for the larger apertures and the transient gating loss increases significantly.

Table III. Antenna Beamwidths and Directive Gain

Antenna Width	Height	8 ft	12 ft	16ft
16 ft	Azimuth BW (deg)	4.16	4.16	4.16
	Elevation BW (deg)	8.33	5.55	4.16
	Gain (db)	30.3	32.1	33.3
24 ft	Azimuth BW (deg)	2.78	2.78	2.78
	Elevation BW (deg)	8.33	5.55	4.16
	Gain (db)	32.1	33.8	35.1
32 ft	Azimuth BW (deg)	2.08	2.08	2.08
	Elevation BW (deg)	8.33	5.55	4.16
	Gain (db)	33.3	35.1	36.3
40 ft	Azimuth BW (deg)	1.67	1.67	1.67
	Elevation BW (deg)	8.33	5.55	4.16
	Gain (db)	34.3	36.0	37.3

4.1.3 Trade-off Results (Clutter Suppression not Preserved)

The trade-off analysis examines the azimuth and the elevation planes separately. Antenna widths from 16 to 40 ft are analyzed, and for each width antenna heights of 8, 12 and 16 ft are considered. The savings in transmitter power relative to that required for the original 24x8 ft antenna are tabulated in dB in Table IV. The change in azimuth beamwidth and the corresponding effects on TOT and on various losses related to the integration of different number of pulses are evaluated individually for the three different elevation apertures. The result for the 40x16 ft aperture is not shown because only one pulse per CPI is available for processing.

In relating the effects of the changes in antenna size on transmitter power, the free space detection range and the other radar parameters have been kept constant. Specifically, azimuth scan rate, operating frequency, antenna sidelobe levels, detection logic, visibility factor and PRF are fixed. The study assumes an azimuth scan rate of 12 RPM, corresponding to 72 degrees/second. This analysis approach is applicable when the clutter suppression and doppler performance are allowed to deteriorate. Such an analysis is applicable only to non-coherent processing where the energy per CPI must be maintained, but the time-on-target is not critical. For a system using pulsed doppler processing, the TOT is also important and the number of pulses transmitted cannot be reduced without adversely affecting doppler resolution and clutter suppression.

In the baseline system, 43% of the TOT for each beamwidth is devoted to scanning the lowest beam. For the baseline system this percentage reflects the time required to transmit a total of 49 pulses. Of these, 32 pulses are processed and 17 are fill pulses, required to ensure suppression of returns from distant clutter. The remainder of the TOT is used to scan three higher beam positions for a total elevation coverage of 35.5 degrees. When the antenna width is increased, the TOT is shortened and the number of pulses available for target detection in the lowest as well as in the higher beams is reduced. Furthermore, as the antenna height is increased, a larger number of elevation beam positions must be scanned to obtain the desired elevation coverage. Since all elevation beam positions must be scanned during each TOT, even less time can be devoted to each elevation position and fewer pulses can be collected.

The overall TOT and the time allocated to each CPI vary in accordance with the antenna beamwidth and the number of sequential elevation scans required for each case. The number of pulses per CPI is adjusted continuously so that, for a given antenna vertical aperture, the percentage of the TOT devoted to scanning each elevation beam is constant. For the 8 foot high antenna 43% of each TOT is allocated to the lowest elevation scan. The percentage devoted to each elevation scan is reduced for the 12 and 16 foot antenna heights because the narrowed elevation beamwidths require more sequential elevation scans per TOT. The 12 foot high antenna requires six sequential scans in elevation to provide the desired elevation coverage of about 35 degrees. For the 16 foot high antenna the number of sequential elevation scans increases to eight.

TABLE IV. Transmitter Power vs. Antenna Size

Clutter Suppression not Preserved

Change in transmitter power in dB required to maintain constant detection performance relative to 24x8 foot antenna

Antenna Width	Height	8 ft	12 ft	16 ft
16 ft		1.2 dB	-0.1	-1.0
24		0.0	-1.2	-2.0
32		-0.7	-1.8	-2.6
40		-1.1	-2.2	N/A

The analysis method that allows for a short TOT results in a non-binary number of pulses processed during each CPI, and, for the larger apertures, may even use non-integral values of the PRI. Furthermore, for the largest antenna apertures the beamwidths become so narrow and the CPIs are so short that the doppler resolution and clutter suppression is totally inadequate. The

results of this analysis show the calculated transmitter power savings that are predicted based solely on considerations of the energy required for detection.

Although the energy requirements for target detection are satisfied, the waveforms and detection logic used in the baseline system (with a 24x8 foot antenna) are not suitable for the larger antennas under consideration. A practical radar using one of these antenna apertures requires a revised configuration, such as dual receive channels, that can support the desired elevation coverage as well as accommodate an adequate number of pulses per CPI.

4.1.4 Antenna Size vs. Transmitter Power (Full Clutter Suppression)

The above section discussed the savings in transmitter power that can be achieved by using an antenna aperture larger than that of the baseline system without regard for adequate clutter suppression. For systems having larger antenna apertures, the shorter TOT and the resulting reduced number of pulses per CPI, translates into poor doppler performance and clutter suppression.

The above trade-off is now repeated under the condition that the number of pulses per CPI is never reduced below a minimum value which meets the clutter performance requirements. Two simultaneous receive channels are utilized to obtain a sufficient number of hits per CPI and still maintain an adequate elevation coverage. The number of processed pulses is never reduced below 24. It is assumed that the 24-pulse transform will give adequate doppler resolution and clutter suppression. For the lowest beam a total of 41 pulses per CPI are used, i.e. a 24-pulse FFT with 17 fill pulses to assure adequate cancellation of returns from distant clutter. The elevation coverage is maintained as close to the initial requirements as possible. The estimated savings in transmitter average power must account for any losses resulting from a reduction in the elevation coverage.

A summary of the results for a range of antenna widths and heights is shown in Table V. Note that for a given antenna height the predicted savings in power for different antenna widths are largely offset by increased losses because of reduced elevation coverage. Larger elevation coverages are treated as savings in transmitter power, whereas narrower coverages are counted as a loss. The larger apertures have narrower elevation beamwidths which result in shorter TOTs. The requirement for at least 41 pulses per CPI in the lowest beam prevents the execution of any additional elevation scans necessary to obtain the full desired elevation coverage during each TOT. The available elevation coverage is therefore reduced and the ensuing loss offsets the advantages of the higher antenna gain of the wider antenna.

It must be emphasized that these results give only the general trend and cannot be taken as accurate predictions of the expected power savings. The exact performance of each system configuration must be calculated using parameters that have been optimized for that particular configuration. A number of different variables affect the performance and for each system configuration all these parameters must be optimized to achieve the best possible overall operation. Only following such optimization can the exact transmitter power savings be determined.

Table V. Summary of Power Savings for Various Antenna Sizes

Antenna Size Width/height Feet	Number of Receivers	Number of Pulses/CPI	Savings in Aver. Power dB	Elevation Coverage Deg
16x8	1	57	-1.4	48.3
24x8	1	49	0.0	35.4
24x12	1	41	3.3	27.5
24x12	2	49	0.5	50.7
24x16	2	49	2.9	35.5
32x8	1	41	0.8	31.3
32x12	2	49	1.5	35.5
32x16	2	41	3.7	31.4
40x8	1	41	1.6	24.5
40x12	2	41	2.1	33.7
40x16	2	41	4.5	24.6

Notes:
Frequency 1.1 GHz
Rotation Rate 12 RPM

4.2 Transmitter and Antenna Collocation

This trade-off study examines the issues related to collocating the transmitter and the antenna, i.e., placing the transmitter on the radar antenna mount. As in all trade-offs for the Affordable Radar Study, collocation is considered for its applicability to the Volume Surveillance Radar.

The principal advantage derived from an on-mount location are lower transmit and receive losses that translate directly into a reduction in the required transmitted power. This reduction in loss is particularly significant for systems using phased array antennas where individual or groups of antenna radiators are fed from separate phase shifters. When solid-state transmit/receive modules are used to drive the antenna radiators, the phase shifting function can be performed at a lower power level prior to the final power amplification in the transmit channel, and after the noise

figure has been established in the receive channel. The two-way loss of the phase shifter, which usually may be quite large, is no longer part of the transmit and receive loss calculations. The overall reduction in loss resulting from moving the transmitter on-mount may be as much as 6 dB or larger.

Although the advantages of an on-mount transmitter are intriguing, a number of factors mitigate against this approach. These include increased antenna weight, and difficulties in all of the following: transmitter maintenance, transmitter cooling, distribution of prime power, prime power stability, and the distribution of drive and control signals to the transmitter modules. All of these issues must be carefully considered in order to make collocation successful and to minimize its potential drawbacks.

In the following discussion of transmitter and antenna collocation only a solid-state transmitter is considered. The on-mount placement of a high-power tube transmitter, such as a klystron or TWT and its associated high voltage modulator, is not deemed to be practical because of weight, high voltage and maintenance factors. A solid-state transmitter, on the other hand, may be conveniently partitioned to match the number of individual groups of antenna radiators; each group of transmit modules feeds the corresponding antenna elements directly. Such a configuration eliminates the need for a power combining network and its associated loss; the energy radiated by the individual antenna elements is combined in space.

To minimize the weight of the on-mount transmitter, the savings in transmit and receive losses can be matched by offsetting reductions in the transmitter output power level. The lower output power will significantly reduce both the number of solid state modules, as well as the amount of required on-mount prime power. Solid state devices are more cost effective when operated at high duty cycles, i.e., at lower peak power levels. The radar system can be designed to utilize waveforms with duty cycles of 5 to 10%, thereby reducing the total number of transmit/receive modules without compromising overall system performance.

A further means of minimizing prime power requirements of on-mount solid state transmit/receive modules is to operate the modules at the highest possible efficiency. At L-Band silicon bipolar devices, operating over a narrow RF bandwidth, can achieve efficiencies of better than 50%. Because of the relatively high PRF used by the Volume Surveillance Radar, the uncompressed pulse widths will be relatively short, probably less than 10 μsec. Such pulse widths will result in low peak junction temperatures, permitting higher peak output power levels than would be possible for long pulse width operation. To achieve the desired operation over a wide RF bandwidth, it may be feasible to use separate output power amplifiers for each of two narrow operating bands. A diode

switch (similar to a transmit/receive switch) at each module output can be used to select the desired transmitted signal.

The transmit/receive module will contain one or more power amplifier chains, a low-noise receiver/amplifier, a low power phase shifter switched between the transmit and the receive paths, as well as necessary control and test circuits. Monolithic microwave integrated circuit (MMIC) technology may be applicable to minimize module size, weight and power consumption.

High reliability transmit/receive modules may provide adequate availability, and at-sea maintenance may not be required for the transmitter. Such a no-maintenance policy is a prime consideration in making an on-mount transmitter acceptable for a shipboard radar.

Air cooling is lighter weight and therefore more desirable than liquid cooling for the on-mount transmitter. However, the dissipated heat can give the radar antenna a high IR signature and make it vulnerable to IR homing missiles. Liquid cooling using an on-mount heat exchanger may not improve the situation significantly. A liquid rotary joint used with an off-mount heat exchanger may solve the IR signature issue, but may introduce serious reliability problems.

4.3 Solid State vs Tube-Type Transmitter

This trade-off study explores the relative merits of a solid state (SS) and a tube-type transmitter from the point of view of the Affordable Radar Study, i.e., with the goal of minimizing the system production cost. The development costs of a solid state transmitter are not considered in this study. The question addressed is whether the use of a SS transmitter in place of the more common tube-type unit may result in overall production cost savings over the Volume Surveillance Radar baseline.

4.3.1. Solid State Transmitter Architecture

A SS transmitter is made up of a large number of individual semiconductor amplifier devices whose outputs are summed into one or several high power terminals. For convenience in mounting, handling and maintenance, a number of individual devices are usually combined into identical modules that become the elementary building blocks of the transmitter. The power output of each module typically falls between one and ten kilowatts. The modules often include a receive channel with low noise amplification, a transmit/receive switch, a phase shifter, and the necessary control logic. Such modules are called transmit/receive modules and are the field replaceable elements of the SS transmitter. The number of modules used in a system depends on its total output power requirement, as well as on its antenna configuration. A full phased array system, providing electronic elevation and azimuth scanning, will use as many modules as array elements, typically

several thousand. For a full array application the power output of each module may be somewhat lower. A radar with electronic scan in elevation scan only, such as the Volume Surveillance Radar, will have tens of elevation terminals. The number of modules used for the elevation scan application may range from as few as ten to about one hundred. The failure of an individual module does not result in a failure of the entire transmitter. In fact, the radar may remain operational even though a number of its modules have failed. By contrast, a tube-type transmitter employs one or several klystrons, TWTs, or similar high-power tubes. The failure of even one output power tube results in a failure or severely degraded operation of the radar and requires an immediate maintenance action.

The ability to replace individual failed modules rather than high power output tubes reduces the life cycle costs of the solid state transmitter compared to those of tube-type transmitters. This advantage may be offset by the initial acquisition costs of the SS transmitter that are often higher than those for a comparable tube-type unit. The costs of the SS transmitter depend critically on the costs of the individual devices which are usually custom designed for the particular application. Furthermore, in order to minimize the total number of devices required and thereby reduce the overall cost, the power output of the bipolar or FET semiconductor device is set as high as the state-of-the-art will permit. The manufacturing yield for the devices may be low which in turn affects their cost. For these reasons the actual production costs of SS transmitters often exceed their original projections, and result in acquisition costs that are not competitive with tube-type designs.

The production costs for a SS transmitter depend critically on the total number of modules produced. In addition to the costs of the individual devices, the costs include module assembly and testing. If warranted by the production volume, these latter functions can be largely automated. For the shipboard surveillance radars, such as the Volume Surveillance Radar, typical production quantities range from 12 to 20 per year, which is not high enough to justify fully automated production setups. Assuming a rate of 20 radars per year, with 44 modules per radar, a production rate (including 10% spares) of 1000 modules per year is obtained. The annual number of solid state microwave semiconductor power devices would be about 12,000 for 400 W devices, and about 25,000 for 200 W devices, which are low numbers for semiconductor production.

4.3.2 Waveforms for Solid State Transmitter

To be cost-effective, the SS transmitter must be able to exploit the special characteristics of solid state devices, i.e. the ability to operate at a high duty cycle, and thereby reduce the total number of devices required for a given average power output. A radar waveform suitable for use with a solid state transmitter

generally differs from that for a tube-type transmitter. For a valid cost trade-off between radars with SS or tube-type transmitters, the waveforms and system parameters may have to be changed to accommodate the special capabilities of the two transmitters. If the original tube-type transmitter is simply replaced by an equivalent solid state unit, a "bottle" type SS transmitter that sums the outputs of a large number of solid state devices into a single output port is required. The cost of such a SS transmitter will most likely be high when compared to the cost of the original tube-type transmitter, and its use will not be economically justifiable. However, by reconfiguring the radar system to use a different waveform and operate at a lower peak power, a SS transmitter, requiring a relatively smaller number of individual modules, may become cost competitive.

A solid state transmitter is best suited for operation with a waveform having a high duty cycle, corresponding to a long pulse width and a high PRF. On the other hand, radars for most tactical applications require a short minimum range and good range resolution. To satisfy these conflicting requirements requires the use of pulse compression, operation at a relatively high PRF, and an uncompressed pulse length that does not exceed the desired minimum range. Although solid state devices are capable of operating at even higher duty cycles, the requirement to keep radar blind ranges and target eclipsing to acceptable values constrains the selected duty cycle to less than about 10%. The use of a high PRF is compatible with pulsed doppler operation.

Pulse compression adds another cost element. Digital pulse compression is particularly attractive because of its flexibility and ability to accommodate and vary the pulse compression codes in rapid succession, which is a desirable anti-jamming feature. However, digital pulse compression also tends to be expensive. Simple pulse compression circuits that use analog delay lines are generally relatively inexpensive.

4.3.3. SS Transmitter Configuration for Array Antenna

Since a solid state transmitter is built up of many individual amplifier devices, it is an advantageous configuration for electronically steered phased array systems. The transmitter can naturally be partitioned into individual transmit or transmit/receive modules each of which feeds an individual or a group of array radiating elements. Placing the final amplification stages close to the array elements results in a significant reduction in the transmit and receive losses of the system, an advantage that cannot be attained using a single tube or a "bottle" type transmitter. The phase shift required in each element, both on transmit and on receive, is now provided at a low power level prior to the final amplification stage. The phase shifters are thereby removed from the high power output transmission line, and

the phase shifter loss is no longer a critical parameter affecting system performance. As a higher insertion loss can be tolerated, lower cost, high loss MMIC phase shifters can be used. The reduction in transmit and receive losses resulting from the use of a transmitter with distributed final amplifier stages reduces the required system average power. This configuration minimizes the required number of solid state devices and is an important step in making a SS transmitter cost competitive.

The Volume Surveillance Radar features electronic steering in elevation and lends itself to a transmitter partitioning wherein each row of antenna elements is fed by individual transmit/receive modules. As suggested above, the phase shift function required in the elevation feed is provided within each module by a MMIC device ahead of the final power amplifier stage. The higher loss of the MMIC phase shifters does not affect the radar performance because it is compensated for by additional low power amplification. The savings in transmit and receive losses compared to an off-mount single-output transmitter can often exceed 6 dB. The reduction in system losses is translated to a comparable reduction in power output. For the Volume Surveillance Radar with an on-mount transmitter, only 7.5 kW rather than 30 kW of average power is required. In addition to the reduction in average power, which itself reduces costs, the elimination of the high power phase shifters also results in significant cost savings.

It should be noted, however, that in n electronic countermeasures (ECM) environment, radar performance is not affected by changes in the receive loss. In jamming, radar performance is established by the effective radiated power at the target. The reduction in power attributed to a reduced receive loss is not available in a jamming environment, because both the signal and the jammer are processed through the same receive channels. For operation in ECM, the SS state transmitter can therefore take advantage only of the reduced transmit loss.

The use of transmit/receive modules in each individual elevation feed simplifies the generation of multiple simultaneous receive beams and permits the use of advanced signal processing techniques such as adaptive beam forming. These features can give the radar important performance advantages without a corresponding increase in the transmitter power requirements.

4.3.4 On-Mount Location for Solid State Transmitter

If the power requirements are low enough, a SS transmitter may be sufficiently light-weight to permit it being placed on the antenna. Since the on-mount position of the SS transmitter results in a considerable saving in the required power, i.e. the lowered transmit and receive losses, it will probably become the preferred location for the SS device. The power supply voltages for the SS devices are much lower than for tube-type transmitters, typically

about 50 Volts, which is more easily handled in the on-mount location.

On-mount transmitter maintenance is a critical issue. The SS transmitter can be made to provide considerable redundancy. For example, in the case of elevation beam steering, each elevation feed could be fed by three SS modules, and a failure of one of the three modules would not result in a critical system failure. Module replacement could be deferred until the end of the operational mission, typically 90 days. If the inherent module reliability is sufficiently high, this deferred maintenance policy would give adequate mission availability and would eliminate any requirement for at-sea maintenance. A high module reliability can be assured by a conservative design based on adequate component reliability and low semiconductor junction temperatures.

Several other critical issues must be solved for a successful implementation of the on-mount SS transmitter. These issues include cooling; prime power supply and power distribution; drive signal and local oscillator distribution, control signal distribution; rotary joint requirements; and receive beam forming. If suitable, inexpensive solutions can be devised for these issues, the on-mount position may be the most cost-effective implementation of a SS transmitter approach.

5. Volume Surveillance Radar Variants

A number of variant configurations have been selected to evaluate the cost savings that can be achieved over the Volume Surveillance Radar baseline. The alternate configurations reflect the results of the trade-off studies, particularly the antenna size versus transmitter power investigation. As the antenna aperture is increased, the required average power is reduced. However, for a number of the designs for the larger antenna apertures, two receive channels must be provided to assure that adequate doppler performance and clutter suppression is preserved. Not all antenna configurations shown in Table V are included. Intermediate antenna sizes, that result in small variations in the system costs, are not considered as candidate variants.

The important characteristics of the different variant configurations are shown in Tables VI & VII. Variants #1 and #2 have the same antenna width, but larger antenna heights, 12 and 16 feet, respectively. To maintain the desired elevation coverage of 35 degrees, Variant #2 must have two parallel receive channels. Variant #3 has the largest antenna aperture considered, 40 x 16 feet. Because of the narrow beam widths of Variant #3, its two receive channels can only support an elevation coverage of 25 degrees. Use of three receive channels would further complicate the antenna design and result in a cost increase.

An additional group of variants are considered in Table VII. They have been included to show the cost savings that can be achieved by relatively small reductions in the baseline performance.

The variants in Table VII employ only a single transmitter. The wide operating bandwidth of the baseline system requires two separate transmitters, a feature that will increase the system costs significantly. For the purpose of a exact comparison of radar features and costs, the baseline system has also been restated with the single transmitter option and appears as Variant #10.

Variants 8 & 9 uses a reduced antenna rotation rate. The original azimuth scan rate of 12 RPM is slowed to 10 RPM, a 17% reduction in scan rate. The slower scan rate permits the use of a larger antenna with a single receive channel, or, alternatively, with two receive channels, but providing the full elevation coverage. The reduced scan rate translates into delayed target detections which may be detrimental to the defense against high speed attackers.

Further reductions in output power may be possible by added signal processing. The use of more powerful signal processing to permit offsetting savings in transmitter power is a possible option for deriving further radar cost reductions.

TABLE VI VOLUME SURVEILLANCE RADAR
VARIANT CONFIGURATIONS

No Degradation in Base Line Performance

<u>ORIGINAL BANDWIDTH CONFIGURATION</u>	BASELINE	#1	#2	#3	#4
ANTENNA SIZE	24 X 8	24 X 12	24 X 16	40 X 16	24 X 8
ANTENNA AREA (SQ. FEET)	192	288	384	640	192
# OF PHASE SHIFTERS	16	24	32	32	44 MOD.
ELEVATION COVERAGE (DEG)	35	35	35	25	35
ROTATION RATE (RPM)	12	12	12	12	12
POWER-AVERAGE (KW)	30	18.1	15.4	10.6	7.5(SS)
POWER-SAVING (dB)	0	-2.2	-2.9	-4.5	-6
XMTR	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT	ON-MNT
OPERATING BANDWIDTH	WIDE	WIDE	WIDE	WIDE	WIDE
# OF RCVR	1	1	2	2	1

TABLE VII VOLUME SURVEILLANCE RADAR VARIANT CONFIGURATIONS

Minimal Degradation in Baseline Performance
*Narrow Bandwidth
*Slower Rotation Rate
*Elevation Coverage

NARROW BANDWIDTH CONFIGURATION	BASELINE	#5	#6	#7	#8	#9	#10
ANTENNA SIZE (FEET)	24 x 8	24 X 8	24 X 12	24 X 16	40 X 16	24 X 12	24 X 8
ANTENNA AREA (SQ. FEET)	192	192	288	384	640	288	192
# OF PHASE SHIFTERS	16	16	24	32	32	24	44 MOD.
ELEVATION COVERAGE (DEG)	35	35	28	35	25	28	35
ROTATION RATE (RPM)	12	12	12	12	10	10	12
POWER-AVERAGE (KW)	30	30	14.0	15.4	8.9	11.7	7.5(SS)
POWER-SAVING (dB)	0	0	-3.3	-2.9	-5.3	-4.1	-6
XMTR	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT
OPERATING BANDWIDTH	WIDE	NARROW	NARROW	NARROW	NARROW	NARROW	NARROW
# OF RCVR	1	1	1	2	2	1	1

5.1 Volume Surveillance Radar with On-mount Solid State Transmitter

An attractive alternative to the off-mount tube transmitter is a Volume Surveillance Radar variant using an on-mount solid state transmitter. Eliminating a significant part of the transmitter and receiver losses, and placing the phase shifters where they do not affect the power output or the system noise temperature, results in savings of about 6.6 dB in system losses, and permits an equivalent reduction in the transmitter average power. The lowered transmitter power makes feasible the on-mount placement of the solid state transmitter.

In the on-mount solid state transmitter variant, each individual antenna row is fed by separate transmit-receive modules, and the transmitted power is combined in space. To assure that no grating lobes are generated when the antenna beam is steered off the boresight axis in elevation, a .57 λ spacing at the highest operating frequency of 1.4 GHz is assumed between the antenna rows.

For the eight-foot high antenna this spacing results in 20 rows. The elevation illumination function is uniform, because the output power amplifiers all have the same output power level. If desired, a tapered illumination function can be used on receive to improve the elevation sidelobes. As in the baseline radar, a Taylor illumination is used in the azimuth plane to obtain -45 dB sidelobes. The uniform antenna illumination results in a 1.3 dB higher antenna gain. When compared to the baseline antenna, the uniform elevation illumination results in a narrower elevation beam width, which, in turn will require scheduling of additional beams to provide the desired elevation coverage.

A 7.5 KW average power solid state transmitter has been assumed for the on-mount solid state variant. The system will have a better performance than is achieved with the 30 KW off-mount unit. Pulse compression is a necessity for a solid state transmitter in order keep the peak power levels as low as possible and to make efficient use of the transistor devices. With an average duty factor of about 7%, the total peak power is 110 KW, and the peak power per row is about 5.5 KW. This requirement can be met by feeding each row with two 3-KW transmit-receive modules. The entire transmitter will consist of 40 modules plus four driver modules that require only the power amplifier stages. Alternatively, each row could be fed by three 2-KW modules. This configuration is likely to result in a higher system reliability and availability, albeit at a somewhat higher cost. The proper sizing of the solid state transmitter requires a detailed design study that is beyond the scope of the present investigation.

A summary of preliminary parameters for the Volume Surveillance Radar variant with an on-mount solid state transmitter is shown in Table VIII, and a loss budget is given in Table IX. The pulse compression loss is included in the range calculation. The losses can be compared with those shown in Table II for the baseline system.

Table VIII. Solid State Transmitter Radar Parameters

Average power	7.5 KW
Peak power	110 KW
Pulse width	6 μs
Duty Factor	7%
Transmitter	On-mount
Module Output, Peak	3 KW
Module Gain	16 dB
Noise Figure	2 dB

The attached Blake chart, Figure 2, gives the detection range on a 1 m^2 Swerling 1 target for the lowest beam of the Volume Surveillance Radar using the 7.5 KW solid state transmitter. The detection criterion of seeing the target on one CPI is identical to that described in Section 3 in the reference calculation for the Volume Surveillance Radar with the off-mount 30 KW transmitter. The free space detection reference range is 154.1 nmi as compared to 128.7 nmi for the base line system, yet the required average power is only 7.5 KW, 25% of that used in the reference system. Part of the increase in the detection range is the result of using a uniform illumination function in the elevation plane. The system noise temperature is also improved by more than 2 dB because of the lowered antenna and receiver losses.

TABLE IX. Loss Budget for Radar with Solid State Transmitter

	Azimuth distribution network	0.6 dB
Total	Antenna Loss	0.6 dB
	Waveguide Xmtr to RJ	0.3 dB
Total	Transmitter/Receiver (Lt/Lr)	0.3 dB
	Pulse Compression (-35 dB SL)	1.0 dB
	Filter matching (-70 dB weight)	2.2 dB
	Range gate straddling	0.8
	Eclipsing	0.7
	Transient gating	1.3
	Filter straddling	0.1
	CFAR	0.8
Total	Signal Processing (Lx)	6.9 dB
	Matching loss (CB)	0.5 dB
	Beam shape loss (Lp)	0.7 dB

PULSE-RADAR RANGE-CALCULATION WORK SHEET (L.V. Blake)		
Radar: VOLUME SEARCH RADAR (ON-MOUNT SS-XMTR) Elevation Angle: 4 Sw.C. 1		P_d = 0.5 P_f = 1.00E-07
A. Computation of T_s	B. Range Factors	C. Decibel Values
(a) Sky Temperature = 70.0 °K Ant. Ohmic Loss L_a = 0.60 dB Antenna Temp. T_a = 122.2 °K	P_{av}(kW) = 7.50 t_f(μs) = 4,116.0 G_t = G_r = σ(sqm) = 1.000 f(MHz) = 1,150.0 T_s(°K) = 324.7 V_o = 1 of 1 CPI C_B = L_t = L_p = L_x =	10 log(P_{av}) = 8.75 10 log(t_f) = 36.14 G_t(dB) = 33.20 G_r(dB) = 33.20 10 log (σ) = 0.00 -20 log(r) = -61.21 -10 log(T_s) = -25.11 $-V_o$(dB) = -13.50 $-C_B$(dB) = -0.50 $-L_t$(dB) = -0.30 $-L_p$(dB) = -0.70 $-L_x$(dB) = -6.90 Rng Eq Cnst = 4.45
(b) Receive Loss L_r = 0.30 dB Equiv. Temp T_r = 20.7 °K		
(c) Noise Figure F_n = 2.00 dB Equiv. Temp. $L_r T_e$ = 181.7 °K	Net Decibels (dB) = 7.52	
	F.S. Detection Range (nm) = 154.1	
Syst. Noise Temp. T_s = 324.6 °K	F.S. Detection Range (km) = 285.5	
Atmosph. attenuation corresponding to free-space range		L_a(dB) = 0.67
First approximation to actual detection range		R_{max}(nm) = 148.3 R_{max}(km) = 274.7
Atmosph. attenuation for first range approximation		L_a(dB) = 0.67
Second approximation to actual detection range		R_{max}(nm) = 148.3 R_{max}(km) = 274.7

Fig. 2 Blake Chart for the Solid State Variant of the Volume Surveillance Radar

If the output power of the radar is used more efficiently for target detection, such as in a detection criterion requiring that the target is seen on at least two of four CPI transmitted on the lowest beam, the visibility factor is 8.4 dB, and the corresponding free space detection range increases to 206.7 nmi.

The 7.5 KW average power output and 50% efficiency modules require a 300 ampere, 50 Volt on-mount power supply, or slip rings rated to handle this current. For a module efficiency of 50%, the power to be dissipated on-mount is equal to the average power output, i.e., 7.5 KW for the example given. These power requirements are sufficiently modest to make the on-mount solid state transmitter a potentially viable configuration.

6. Cost Analysis

Qualitative notions and rules of thumb, such as "it costs more to build a 3-D radar with given range than a 2-D radar having the same detection range", are useful as general guidelines to developing an overall affordable radar concept. However, for reliable comparisons and more detailed production cost evaluations of different system configurations and design approaches, it is necessary to resort to more quantitative ways of estimating cost. The costs of the alternative radar configurations must be estimated with sufficient accuracy to permit pinpointing of the most cost- effective designs.

Once the decision to quantify radar costs has been made, a number of alternative approaches must be considered. There are advantages to considering full life cycle costs when comparing alternative radar designs since these costs represent the total cost to the Navy for the radar system. There are a number of major disadvantages, as well, in trying to consider life cycle costs. First, quantifying of future operational and maintenance (O & M) costs is difficult to accomplish even when a production version of a radar is available. At the preliminary design stage, such as in the case with the Volume Surveillance Radar, O & M costs are even more nebulous. Secondly, it often has been claimed that O & M costs are given little weight in system acquisition decisions, because they are so difficult to estimate and because they are future costs which, in addition are not funded by the procurement agency. Moreover, if R & D costs and/or production costs will be so high that a program is either not started, or canceled before going into production, it is meaningless to be concerned with O & M costs.

6.1 Cost Evaluation Model

Given the preliminary nature of the VSR design, it was decided to estimate only production costs. The basic approach was to start with an existing Cost Evaluation Model and to update its results with engineering judgment.

The Cost Evaluation Model selected for this program was the Tecelote model [1]. Like other cost models, it does not attempt to estimate overall system cost directly. Instead, the system is broken down into more manageable units by means of a Work Breakdown Structure (WBS). In the case of a radar, the WBS is based on subsystems such as the antenna, transmitter, exciter, receiver, etc.

Cost Estimating Relationships (CER's) have been developed for each subsystem as follows:

(1) A list of factors, which are potential cost drivers, is developed. For example, for a tube type transmitter, average power, peak power, duty cycle and frequency might all be cost drivers.

(2) Data are collected for subsystem costs for various radars.

(3) Multiple regression techniques are used to ascertain which of the potential cost drivers actually have a significant effect on subsystem cost.

For tube transmitters, for example, the two important cost drivers are average power and duty cycle, with the following relationship:

$$\text{XMTR COST} = 124.1 \times (\text{AVE.POWER})^{0.452} \times (\text{DUTY CYCLE})^{-0.12} \quad (1)$$

In the above equation, the cost is in thousands of FY 1977 dollars and is the average unit cost for a production quantity of 100. Final cost estimates are scaled to the appropriate fiscal year and production size.

In addition to estimates for specific subsystems, costs for interconnections and cables/waveguides are estimated as 1.6% of the total of the hardware costs of a single system. Assembly and test costs are set at 5% of all other costs of the single system. Also, initial tooling and test equipment (ITTE) is estimated by the following relationship:

$$\text{ITTE COST} = 4.855 \times (\text{PRODUCTION RATE})^{0.482} \times \Sigma(\text{ALL OTHER COSTS}) \quad (2)$$

where:
production rate is in units of copies/month, and

the final term is the sum of all costs across the entire production run of all copies of the radar

For purposes of this study the production rate and the production year are kept fixed for variants of the Volume Surveillance Radar. Hence the ITTE costs are a fixed percentage of the costs of the individual variants and do not affect the relative costs of these variants. The ITTE costs are therefore neglected in the cost comparison for the different Volume Surveillance Radar configurations.

6.2 Cost Model Calibration

As a check of the cost model, estimates were made for the original version of the AN/SPS-49, circa 1978, as well as for the 1991 AN/SPS-49(V5). According to NAVSEA contract #78-C-7080 the unit costs of the SPS-49 in FY 78 dollars was $1,271,752. The corresponding production cost estimate produced by the cost model was $1,425,500, which is 12% higher than the NAVSEA contract.

Table X gives a comparison of the system parameters for the 1978 version of the AN/SPS-49 and the 1991 AN/SPS-49(V5). Cost model results for the latter are shown in Table XI. In the case of the

AN/SPS-49(V5), there is considerable discrepancy between the model's estimate of $2,967K and the current price of about $3,500K to $4,000K. This discrepancy arises predominantly because of the difference between the model's estimate of $108K for signal processing and the contractor's cost of about $1,200K. Clearly, signal processing costs for present day radars must be estimated by methods other than the cost evaluation model. The cost model's estimate for the AN/SPS49(V5) has therefore been revised based on historical data from government and industry sources. The revised AN/SPS-49(V5) cost estimates appear in Table XI. Specifically, the signal processor costs have been increased significantly.

Table X. Parameters for Two AN/SPS-49 Versions

PARAMETER	AN/SPS-49(V1) 1978	AN/SPS-49(V5) 1991
Pulse doppler	No	Yes
No. of A/D converters	1	2
A/D conversion rate	0.625 MHz	0.67 MHz
Doppler filter type	Transversal	Convolver
Doppler data rate	0.625 MHz	0.67 MHz
No. of doppler bins	16	6
No. of pulse comp. lines	1	2
Exciter phase stability	Low	High
Signal processing rate	0.625 MHz	1.34 MHz
Clutter map	No	Yes
No. of MBits in map	N/A	1.4
Type of map	N/A	Random access
Detection complexity	Medium	High

TABLE XI. FY-91 COST ESTIMATES FOR THE AN/SPS-49(V5)

LEARNING= 90% — QUANTITY= 20
PRIME MISSION EQUIPMENT - RADAR — UNIT COST in $K

	COST MODEL	REVISED ESTIMATE
ANTENNA	419	419
TRANSMITTER	1,468	1,468
EXCITER	449	449
RECEIVER	238	238
PULSE COMPRESSION	15	15
SIGNAL PROCESSOR	108	1,200
CONTROL/DISPLAY	81	81
CABLE/W.G	44	62
ASSEMBLY & TEST	141	196
TOTAL	**$2,967**	**$4,131**

AN/SPS-49(V5) ACTUAL COSTS IN FY-91-$3.5M TO $4M

6.3 Costs of Volume Surveillance Radar Variants

Tables VI and VII, Section 5, showed the changes from the baseline configuration which resulted in variants to the Volume Surveillance Radar baseline configuration. One or more of the following were changed in each modification:

Average XMTR Power (KW)
Aperture (Square ft.)
Number of Phase Shifters
Number of Receiver Channels
On mount Solid State Transmitter

The more promising results of the trade-off studies were used to configure Volume Surveillance Radar variants and cost estimates were prepared to evaluate the potential cost savings of these changes. All production costs have been calculated for FY-92, a production lot size of 15, a production rate of one per month, and a learning curve of 90%.

A summary of the estimated costs of the different variants of the Volume Surveillance Radar is shown in Table XII for both 12 and 10 RPM azimuth scan rates, as well as for different combinations of antenna size, number of receive channels, and operating bandwidth. The production cost of the baseline VSR is estimated at $8M. Variants showing negative savings have an increased production cost relative to the baseline.

Reduced system performance, such as narrowed operating bandwidth, slower azimuth rotation rate and decreased elevation coverage, results in cost savings of 16.9 to 32.5% as compared to the original full performance baseline. The largest savings (22%) accrue from the narrower operating bandwidth because it requires only a single transmitter. If the costs of the other reduced performance configurations are compared against a baseline which has also been adjusted for the narrower operating bandwidth, the projected savings are 7.8% to 10.5%. Furthermore, variants requiring the use of two receivers show savings smaller than the 22% of the adjusted baseline system.

The solid state Variant #4 shows a cost saving of 16.4%. The cost analysis is based on a on-mount transmitter consisting of 44 transmit-receive modules at an estimated production cost of $20K each. The overall transmitter cost is assumed to be three times that of the modules alone. For the narrow bandwidth configuration, an individual module cost of $18K is assumed. These cost estimates are very preliminary and must be validated based on a more detailed design study.

TABLE XII VOLUME SURVEILLANCE RADAR COST ESTIMATES

No Degradation in Base Line Performance

	BASELINE	#1	#2	#3	#4
ORIGINAL BANDWIDTH CONFIGURATION					
ANTENNA SIZE(FEET)	24 X 8	24 X 12	24 X 16	40 X 16	24 X 8
ANTENNA AREA (SQ. FEET)	192	288	384	640	192
# OF PHASE SHIFTERS	16	24	32	32	44 MOD.
ELEVATION COVERAGE (DEG)	35	35	35	25	35
ROTATION RATE (RPM)	12	12	12	12	12
POWER-AVERAGE (KW)	30	18.1	15.4	10.6	7.5(SS)
POWER-SAVING (dB)	0	-2.2	-2.9	-4.5	-6
XMTR	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT	ON-MNT
OPERATING BANDWIDTH	WIDE	WIDE	WIDE	WIDE	WIDE
# OF RCVR	1	1	2	2	1
COST ESTIMATE K$					
ANTENNA (ELEV STEERING)	1,800	2,045	2,382	2,958	1,500
XMTR (2 XMTRS = 1.5*BASEXMTR)	3,771	3,001	2,790	2,363	2,640
EXCITER (SYNTHESIZER)	894	894	894	894	894
RCVR	52	52	104	104	52
SIGNAL PROC.	900	900	1,200	1,200	1,100
CONTR & DISPL	88	88	88	88	88
CABLE & Wg (1.6% OF HWDE)	120	112	119	122	100
ASSY & TEST (5% OF OTHER COSTS)	381	355	379	386	319
ESTIMATED COST (K$)	8,006	7,446	7,957	8,115	6,693
DELTA COST vs. BASELINE (K$)	0	(560)	(50)	109	(1,313)
SAVINGS - PERCENT	0.0%	7.0%	0.6%	-1.4%	16.4%

TABLE XII (cont.) VOLUME SURVEILLANCE RADAR
COST ESTIMATES
VARIANT CONFIGURATIONS
Minimal Degradation in Baseline Performance

*Narrow Bandwidth
*Slower Rotation Rate
*Elevation Coverage

	BASELINE	#5	#6	#7	#8	#9	#10
NARROW BANDWIDTH CONFIGURATION							
ANTENNA SIZE (FEET)	24 X 8	24 X 8	24 X 12	24 X 16	40 X 16	24 X 12	24 X 8
ANTENNA AREA (SQ. FEET)	192	192	288	384	640	288	192
# OF PHASE SHIFTERS	16	16	24	32	32	24	44 MOD.
ELEVATION COVERAGE (DEG)	35	35	28	35	25	28	35
ROTATION RATE (RPM)	12	12	12	12	10	10	12
POWER-AVERAGE (KW)	30	30	14.0	15.4	8.9	11.7	7.5(SS)
POWER-SAVING (dB)	0	0	-3.3	-2.9	-5.3	-4.1	-6
XMTR	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT	OFF-MNT	ON-MNT
OPERATING BANDWIDTH	WIDE	NARROW	NARROW	NARROW	NARROW	NARROW	NARROW
# OF RCVR	1	1	1	2	2	1	1
COST ESTIMATE K$							
ANTENNA(ELEV STEERING)	1,800	1,800	1,944	2,382	2,897	1,880	1,500
XMTR(ONE XMTR)	3,771	2,514	1,785	1,860	1,450	1,642	2,376
EXCITER(SYNTHESIZER)	894	501	501	501	501	501	501
RCVR	52	52	52	104	104	52	52
SIGNAL PROC.	900	900	900	1,200	1,200	900	1,100
CONTR & DISPL	88	88	88	88	88	88	88
CABLE & WG(1.6% OF HWDE)	120	94	84	98	100	81	90
ASSY & TEST (5% OF OTHER COSTS)	381	297	268	312	317	257	285
ESTIMATED COST (K$)	8,006	6,246	5,622	6,545	6,656	5,401	5,992
DELTA COST vs. BASELINE (K$)	0	(1,760)	(2,385)	(1,461)	(1,350)	(2,605)	(2,014)
SAVINGS - PERCENT	0.0%	22.0%	29.8%	18.3%	16.9%	32.5%	25.2%

+ Two XMTR'S

7. Preliminary Conclusions

The Affordable Radar Study has explored the possibility of reducing the production cost of a radar system while maintaining a constant level of performance. With this restraint, cost savings can only result from changes in the system configuration whereby the same overall performance requirements are allocated to the various subsystems in a more cost effective manner. The designs of the major subsystems, the antenna, transmitter and receiver/signal processor, have been examined and trade-off studies have been conducted aimed at optimizing the assignment of requirements to these subsystems.

Any cost savings derived by this procedure result from differentials in the cost versus performance relationships among the individual subsystems. Such cost differentials can be expected to be relatively small. This result could be anticipated, as significant cost savings would have been readily apparent and therefore would have been incorporated in the original system design approach.

Savings identified in this study range from less then 5% to as much as 32%. Most of the larger savings reflect system variants that also result in a small reduction in system performance.

The largest cost savings for a configuration that still maintains full performance results from the use of a solid state on-mount transmitter. The estimated production cost savings of 16.4% must be validated by a more thorough design study of the solid state transmitter and an examination of the feasibility of mounting it on the antenna.

A summary of preliminary conclusions drawn from the Affordable Radar Study to date is shown in Table XIII.

7.1 Antenna Size vs. Transmitter Average Power

The use of a larger antenna aperture and the corresponding reduction in the required transmitter power to maintain a constant detection range results in a reduction in the costs of the transmitter. However, for the largest antenna sizes the cost increase of the antenna exceeds any savings accruing from the lowered transmitter power. Furthermore, the larger antenna results in narrower azimuth and elevation beamwidths, shorter time-on- target (TOT), fewer pulses per TOT, and narrower elevation coverage.

In order to maintain the doppler performance and clutter rejection of a radar using coherent (doppler) processing, the TOT cannot be shortened. Hence an increase in the antenna aperture requires the addition of extra receive channels. The costs of the additional receivers and signal processing limit any cost benefits that can be derived from the reduction in the transmitter power. The narrower elevation beamwidth reduces the elevation coverage per scan. If the original elevation coverage is to be maintained, multiple beams and/or additional scans may be required.

When the doppler performance and clutter suppression are not of primary importance, as in the case of incoherent processing, having fewer pulses per TOT may become acceptable. Under these circumstances, the shorter TOT associated with the narrower azimuth beamwidth does not affect system performance, and larger cost reductions may result from the use of the smaller transmitter.

7.2 Tube-type vs. Solid State Transmitter

For transmitters having an equal power output, a solid state unit appears to be more expensive than an comparable tube-type transmitter. Solid state transmitters become more cost effective when operated at a high duty cycle. However, the radar waveforms cannot be adjusted enough to make the solid-state unit cost competitive (i.e. the duty cycle cannot be made high enough).

7.3 Off-mount vs. On-mount Transmitter Location

Considerable savings in transmitter output power can be achieved by placing the unit on the antenna mount. The reduction in power reflects the elimination of transmit and receive losses associated with the rotary joint and transmission lines, and, in the case of elevation steering, with transmit and receive phase shifters. However, except for the smallest shipboard navigation or short- range surface search radars, the tube-type transmitter is too large for on-mount location. Furthermore, at sea maintenance requirements of the tube-type transmitter also argue against locating the transmitter on-mount.

The reduced transmitter power required by an on-mount location may make a solid-state on-mount transmitter practicable. The inherently high reliability of solid-state modules reduces the maintainability requirements and can eliminate at sea maintenance. The smaller, on-mount solid-state transmitter may result in a cost advantage relative to the off-mount tube-type unit. However, the cost impact of other factors associated with the on-mount positioning must be carefully considered. These include the original development costs that are usually high for solid state transmitters as well as the costs associated with the location of the power supplies, power and drive signal distribution, module cooling, etc.

7.4 Cost Estimation

Reliable production cost estimation depends upon the availability of an up-to-date cost baseline of radars using similar technology. The extrapolation of production costs from the baseline to significantly larger or smaller systems, or to systems using different technologies will result in inaccurate cost estimates and unreliable comparisons between the costs of the different system versions if an accurate cost baseline is not available.

Table XIII Summary of Conclusions (3D L- Band Radar)*

ANTENNA SIZE vs. TRANSMITTER AVERAGE POWER

- For systems with non-coherent processing a larger antenna & lower transmitter power result in reduced costs
- For systems with coherent processing these cost savings accrue only if the available TOT supports the required doppler processing
- If an extra receive channel is required to provide longer TOT in a coherent system, the added cost negates most cost savings

ON-MOUNT vs. OFF-MOUNT TRANSMITTER

- On-mount design reduces losses and saves considerable transmitter power
- Tube transmitters require high power phase shifters and elevation power dividers which are generally too large for on-mount location
- At-sea maintenance is a serious problem for on-mount tube transmitters with high voltage and liquid cooling
- Reduced power requirements make solid state transmitters more cost effective
- High solid state module redundancy may eliminate at-sea maintenance
- On-mount SS transmitters have a significant cost advantage over off-mount tube transmitters

FOR MINIMAL REDUCTION IN BASELINE PERFORMANCE A COST SAVINGS OF UP TO 32% IS POSSIBLE

- 12 RPM to 10 RPM
- 2 vs 1 Transmitters
- 35° to 25° Elevation Coverage

* FOR PRODUCTION COSTS ONLY

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